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Assessment of utility energy storage options for increased renewable energy penetration

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ABSTRACT

Renewable energy technologies are expected to take the leading role in the forthcoming energy generation portfolio in order to achieve sustainable energy generation. The major constraints for increasing penetration of renewable energy sources is their availability and intermittency, which can be addressed through energy storage when available and energy use when needed. This work reviews the energy storage technologies and gives an up to date comparative summary of the performance parameters of the major energy storage options. The parameters compared here include efficiency, energy capacity, energy density, run time, capital investment costs, response time, lifetime in years and cycles, self discharge and maturity of each energy storage option. The choice of storage system will depend on individual requirements, and may even incorporate more than one energy storage system to increase the energy storage capacity and improve energy security.

Contents

1. Introduction

Energy for electricity generation has traditionally been generated from fossil fuels, where the fuel can be stockpiled for immediate access to energy when needed, representing a concentrated, stable form of energy. Hydro and geothermal renewable

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energy sources are similar in that they too are readily accessible stable forms of energy. Intermittent renewable energy sources, such as wind, wave, tidal and solar, are unable to be stockpiled and must be used as available or, otherwise they will be lost energy potentials. These energy sources are an immediate form of energy that must be converted into a different form to be stored. In transitioning to higher fractions of renewable electricity generation it is essential that adequate storage technologies are employed, allowing immediate resources to be captured and kept until they are required. If suitable storage methods can be advanced, intermittent renewable energy sources, hydro and geothermal power can replace fossil fuels in a sustainable energy grid. This also offers improved efficiency as maximum demand may only last for several hours each day, which traditionally has led to over-designed and expensive power plants made to run at a steady state production much higher than the average base load electricity demand [1]. Energy storage is also beneficial for shorter duration applications including grid stabilisation, grid operational support, stable power quality and reliability, and load shifting. With modern technical equipment, the security of an uninterrupted power supply has become of extreme importance.

There are several established and a large number of developing technologies offering significant potential to enable energy storage for electricity production. Economically viable storage of energy requires conversion of electricity and storage in some other energy form, which can then be converted back to electricity when needed [1]. There are largely four classes of energy storage systems, namely mechanical, electrical, thermal and chemical systems. Each class contains several technologies for consideration outlined in detail in this review and assessed in reference to utility scale power supply. Despite the opportunity offered by the energy storage systems to increased energy stability and reliability of the intermittent energy sources, in 2009 there were only four energy storage technologies (sodium–sulphur batteries, pumped hydro energy storage, compressed air energy storage, and thermal storage) with a globally installed capacity exceeding 100 MW [2]. The opportunities for significant improvement in development of the energy storage systems are apparent. In this work a comprehensive review and comparison of the characteristics of each energy storage technology is performed with the aim to critically assess the most appropriate technologies for application to power quality management, load shifting and energy management. A review of the systems and their performances is required for improvement of the rate at which these technological solutions are introduced in the market.

2. Storage technologies

The energy storage technologies can be classified in four categories depending on the type of energy stored, as shown in Fig. 1. They consist of mechanical, electrical, thermal and chemical energy storage technologies each offering different opportunities, but also consisting of own disadvantages [3]. In the following, each method of electricity storage is assessed and the characteristics of each technology, including overall storage capacity, energy density (the amount of energy stored per kilogram), power density (the time rate of energy transfer per kilogram) and efficiency of round trip energy conversion are compared.

2.1. Mechanical energy storage

Mechanical energy storage options include storage in the forms of potential and kinetic energy. The potential energy storage consists of compressed air energy storage (CAES) and pumped hydro energy storage (PHS), while the kinetic energy storage is in flywheels.

2.1.1. Compressed air energy storage

CAES technology is based on storage of energy as the elastic potential of compressed air. Excess energy is used to run air compressors to pump air into underground caverns or above ground storage tanks, where the air is stored under pressure. The compressed air is traditionally used with natural gas for increased efficiency, but can also be used alone where the expansion volume and adiabatic pressure change can generate power in a gas turbine (AA-CAES) [4,5], however the energy content is low [6]. Operating pressures are 40–70 bar at near ambient temperatures [7]. There are five major components of CAES consisting of motor/generator, air compressor of two or more stages, turbine train, cavity or container for storage of compressed air, controls and auxiliaries.

The capital cost of the CAES systems depends on the required air storage volume and construction of the air storage infrastructure. For this reason, underground CAES systems are the most cost-effective options, with the potential to store up to 400 MW or 8–26 h of discharge. The cost of CAES is about half that of lead-acid batteries, adding 3–4 c/kWh [8]. However, underground systems require finding and verifying the air-tight storage integrity of an appropriate geological formation. Natural gas storage caves are ideal as they benefit from geostatic pressure. They also suffer from long construction times and are only suitable at large scale. Above-ground systems have a much lower capacity, 3–15 MW or 2–4 h of discharge but are free of the underground constraints [9]. Both systems have moderate energy densities [10].

CAES has repeatedly been shown as one of the most suitable technologies for storing large amounts of energy (>100 MW) for utilities [1,4]. There are currently two first generation CAES plants in operation, one in Huntorf, Germany where 290 MW plant was constructed in 1978 [11] and the second in Alabama, USA with 110 MW plant constructed in 1991 [5].

2.1.2. Pumped hydro energy storage

The pumped hydro energy storage system (PHS) is based on pumping water from one reservoir to another at a higher elevation, often during off-peak and other low electricity demand periods. When electricity is needed, water is released from the upper reservoir through a hydroelectric turbine and collected in the lower reservoir [9]. The storage capacity is a function of the height of the fall of water and volume of water available. These two variables are also the largest restrictions on the technology as suitable sites must have significant differences in elevation between upper and lower reservoirs with the available space to build two large dams [7]. However, other possibilities include underground pumped hydro energy storage using flooded mine shafts and using the ocean or open seas as the lower reservoir.

Pumped hydro energy storage is the largest capacity and most mature energy storage technology currently available [9] and for this reason it has been a subject of intensive studies in a number of different countries [12,13]. In fact, the first central energy storage station was a pumped hydro energy storage system built in 1929 [1]. Currently, over 129 GW is in operation globally at over 200 installations, making it the most common storage for high power applications. Deregulation and environmental concerns related to building large dams have influenced decline in popularity of the pumped hydro energy storage systems, however in recent years increased demand for electrical energy storage installation rates are increasing again [1].

Installations of individual pumped hydropower stations range up to 4000 MW with typical ratings around 1000 MW, operating at 75–85% efficiency with fast response times long plant lives in excess of 50 years. Pumped hydropower system is a stable long-term storage option for the intermittent renewable energy sources [1].

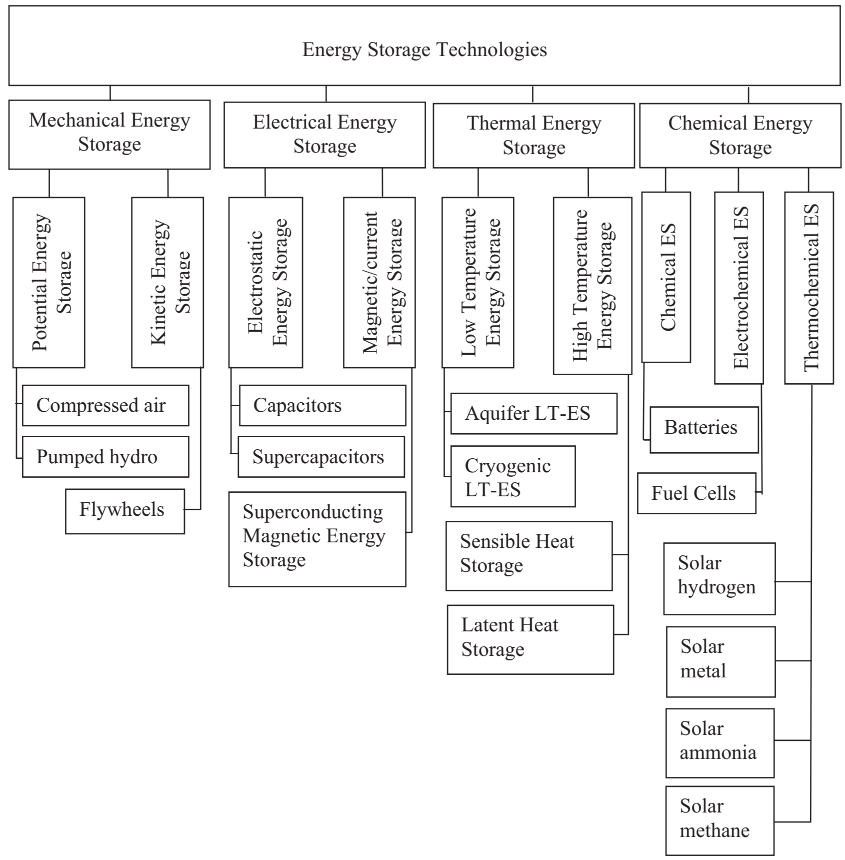

Fig. 1. Classification of the major energy storage technologies.

Pumped hydro and compressed air energy storage systems have the lowest investment risk with respect to the cost per kilowatt hour of electricity produced and the lowest levelised cost of delivered energy, comparable with combined cycle gas turbines [9]. However, these two technologies are associated with large capital cost requirements, restraints to selection of suitable sites and long construction time making them only suitable for large scale [14]. They both also have low energy density [9] and typically result in long transmission distances [15]. It should be also kept in perspective that pumped hydro energy storage system is a net consumer of electricity as it takes more energy to pump the water uphill than is generated during the fall of water, hence the benefit of pumped hydro energy storage comes from storing power generated during low demand, which is released when demand is high [16].

Due to the significant advantages and working history of this method of energy storage, there are many working examples of pumped hydro energy storage systems exceeding 200 MW installed capacity worldwide including Bath County, USA (2710 MW), Kannagawa, Japan (2700 MW), Guangzhou, China (2400 MW) and Lac des Dix, Switzerland (2009 MW) [17].

2.1.3. Flywheels

Flywheels store energy in the angular momentum of a spinning mass. They are charged with a spin of a motor, while energy discharge is achieved through the same motor acting as a generator to produce electricity. The total energy potential is a function of the size and speed of the rotor, while the power rating is a function of the motor-generator.

The first generation flywheels are only suitable to shorter energy duration systems, not generally for large-scale systems, as there are restrictions to the storage capacity. Existing systems have high efficiencies, around 93% with lifetimes of 20 years, high power density, quick recharge and fast response times [9]. Typical applications are for high power, short duration requirements. It has also been demonstrated that a potential application of flywheels is to achieve smoothing effect on the output from wind turbines, stabilising power supply [10]. Advanced flywheels capable of storing large amounts of electricity are currently under development. When compared to batteries, flywheels have a major advantage of long lifetime with ability to provide hundreds of thousands of full discharge cycles. The disadvantage of flywheels is a relatively low energy density, large standby losses and potentially dangerous failure modes [14].

2.2. Electrical energy storage

Electrical energy storage can be achieved in the forms of electrostatic, such as capacitors and supercapacitors, or magnetic/current storage including superconducting magnetic energy storage (SMES).

2.2.1. Capacitors

Capacitors operate by storing energy in an electric field between two electrodes (metal plates) separated by an insulating material called the dielectric. The storage is promoted with increasing electrode surface area and reduced thickness of the dielectric. Capacitors are limited in their energy storage potential due to low capacity and energy density [18] and have been superseded for large scale energy storage applications by supercapacitors.

2.2.2. Supercapacitors

A supercapacitor (also known as an ultracapacitor) is an electric double-layer capacitor (EDLC). It is an advanced capacitor, operating on the same principles as a standard capacitor, but with highly

porous carbon materials having a very large specific surface. Comparing to the capacitors, in the supercapacitors, the dielectric is replaced by electrolyte ionic conductor, and a much lower separation distance is achieved between the electrodes.

EDLC have extremely high power density, high cycle life (over 100,000 cycles), quick recharge without the risk of overcharging and wide temperature operating range (−40 to 70 °C) [18]. They have been shown to decrease voltage and power fluctuations when integrated with grid connected fixed-speed wind generators [19,20]. However, they are expensive, with low energy density and, due to variations in voltage during discharging, require power electronics, adding to the level of system complexity [14].

2.2.3. Superconducting magnetic energy storage system

A superconducting magnetic energy storage (SMES) system applies the magnetic field generated inside a superconducting coil to store electrical energy. Its applications are for transient and dynamic compensation as it can rapidly release energy, resulting in system voltage stability, increasing system damping, improving the dynamic and static stability of the system [15]. SMES DC resistance is nearly zero, resulting in no energy losses. Conversion energy efficiency in the SMES system is around 95% [15].

SMES is a high power technology, with higher power density than other devices for similar purposes [21], however it is expensive, with low energy density and large parasitic energy losses [14]. System limitations arise from the high cooling requirements, sensitivity to magnetic field environments, current strength and magnetic field changes [15].

2.3. Thermal energy storage

The thermal energy storage systems comprise of low and high temperatures thermal options. The low temperature thermal options can be divided into aquifer low temperature energy storage (AL-TES) and cryogenic energy storage (CES). AL-TES energy storage is not used to store energy for electricity generation so will not be further discussed.

Cryogenic energy storage is a developing technology, using off-peak power or renewable energy sources to generate cryogenic fluid, which can then be used in a cryogenic heat engine to generate electricity. As this technology is still under development, it has not yet been proven, but it is expected to have relatively high energy density, low capital cost per unit energy, and a relatively long storage time. However, due to the current high energy consumption of air liquefaction, it has low round trip efficiency at only 40–50% [1].

High temperature thermal energy storage (HT-TES) options are classified as either sensible or latent heat storage. Sensible heat storage system applies heating of mediums, such as steam and hot water accumulators, graphite, concrete, molten salt and hot rocks, to store energy without phase change of the medium [22]. Heat is recovered when needed, to produce water vapour and drive a turbo-alternator system. The sensible heat storage method is becoming popular as costs for development are relatively low and manufacturing is simple, however the energy density of this method of thermal storage is lower than for other thermal technologies [23].

Latent heat systems use high temperature phase changing materials, including paraffin, inorganic salts and metals, to store heat [22,24]. These systems involve solid–solid or solid–liquid transformation of the material at constant temperature. Solids are transitioned into liquid or undergo crystal transition during accumulation of energy and reverse back to the original solid state during retrieval. Heat is transferred using a heat transfer fluid. Latent heat materials have a high heat and energy density, storing between 5 and 14 times more heat per unit of volume than sensible heat storage materials [23]. Most phase change materials are non-toxic, with long cycling lives and undergo small volume changes during the phase change [25]. The latent heat storage systems have found particular use with the solar thermal power. The advantage of thermal storage from concentrating solar thermal power is that the energy is collected and stored as heat directly, without conversion to electricity, which significantly increases the round trip efficiency of the process [2]. Most phase change materials have low thermal conductivity, which results in slow charge and discharge rates [22].

2.4. Chemical energy storage

Chemical energy storage can be further classified into electrochemical and thermochemical energy storage. The electrochemical energy storage refers to conventional batteries, such as lead-acid, nickel metal hydride, lithium ion and flow batteries, such as zinc bromine and vanadium redox and metal air batteries. Electrochemical energy storage is achieved in fuel cells, most commonly hydrogen fuel cells, but also include direct-methanol, molten carbonate and solid oxide fuel cells. The thermochemical storage options include solar hydrogen, solar metal, solar ammonia and solar methane dissociation–recombination methods. The following summarises the most widespread chemical energy storage options, which include the different options of batteries and fuel cells. The other chemical energy storage options, such as the thermochemical storage technologies, although promising, are still at an infant development stage and are not included in this review.

2.4.1. Lead-acid battery (Pb-acid)

Pb-acid battery cells consist of spongy lead anode and lead acid cathode, immersed in a dilute sulphuric acid electrolyte, with lead as the current collector. During discharge, lead sulphate is the product on both electrodes. Sulphate crystals become larger and difficult to break up during recharging, if the battery is overdischarged or kept discharged for a prolonged time period. Hydrogen is produced during charging, leading to water loss if overcharged [26].

Pb-acid batteries are a mature technology, with over a century of operation. They are the most widely used electrical energy storage technology worldwide. Their popularity is result of their wide availability, rugging and reasonably low cost. The disadvantages of the Pb-acid batteries are their weight, low specific energy and specific power, short cycle life (100–1000 cycles), high maintenance requirements, hazards associated with lead and sulphuric acid during production and disposal, and capacity drop at low temperatures [14].

2.4.2. Sodium–sulphur battery (Na–S)

Na–S batteries use a high-temperature reaction between sodium and sulphur, separated by a beta alumina electrolyte. These batteries have an excellent cycle life, high energy density and are relatively mature, with over 55 installations worldwide in 2003 [14]. With a pulse power (up to 30 s) rating at over six times their continuous rating, these batteries are ideally suited to manage power quality and peak shaving applications [1]. The disadvantages of Na–S batteries are their high cost, high self-discharge per day and high temperature requirements for operations [14].

2.4.3. Flow batteries

Flow batteries store the energy in external electrolytes, which are electro-active materials used to store and then convert the chemical energy directly into electricity. They can be divided into redox (all vanadium, vanadium–polyhalide, vanadium–polysulphide, iron–chromium, hydrogen–bromine) and hybrid (zinc–bromine and zinc–cerium) [27]. The flow batteries are scalable for large applications, with high energy and power density

and are easy to upgrade. However, there is high cost associated with these batteries and they are still immature for utility applications. Some of them, such as Zn–Br have the added complications dealing with corrosive and toxic materials [14].

2.4.4. Nickel cadmium (Ni–Cd) and nickel metal hydride (Ni–MH) batteries

Ni–Cd batteries use nickel oxyhydroxide for the cathode and metallic cadmium as the anode with a potassium hydroxide as an electrolyte. These types of batteries were very popular between 1970 and 1990 but have been largely superseded by Ni–MH due to inferior cycle life, memory effect, energy density and toxicity of the cadmium in Ni–Cd, compared to Ni–MH. Ni–MH also have the advantage of improved high rate capability (due to the endothermic nature of the discharge reaction), and high tolerance to overdischarge [28]. Ni–MH use nickel oxyhydroxide for the cathode, with a potassium hydoxide electrolyte and a hydrogen-absorbing alloy usually alloys of lanthanum and rare earths serving as a solid source of reduced hydrogen which can be oxidised to form protons.

Ni–Cd and Ni–MH batteries are mature technologies, relatively rugged with higher energy density, lower maintenance requirements and better cycle life than Pb-acid batteries. They are, however more expensive than lead-acid batteries, with limitations on the long term cost reduction potential due to material costs. In addition, Ni–Cd batteries contain toxic components (cadmium) making them environmentally challenging [14].

2.4.5. Lithium ion (Li-ion) batteries

Li-ion batteries are largely cobalt or phosphate based. In both embodiments lithium ions move between the anode and cathode to generated current flow. Li-ion batteries have a high energy to weight ratio, no memory effect and low self-discharge. Prices may be high and increasing penetration may push prices higher as limited lithium resources are depleted [26].

2.4.5.1. Cobalt based Li-ion batteries. Cobalt-based Li-ion batteries have high efficiency, energy and power density. Disadvantages include high cost due to the limited availability of cobalt, safety concerns and the need for sophisticated battery management [14].

2.4.5.2. Phosphate based Li-ion batteries. The phosphate based Li-ion batteries have higher efficiency than cobalt based Li-ion while maintaining energy and power density nearly as high as cobalt-based at lower cost. Phosphate-based Li-ion battery is a more recent technology than cobalt-based, requiring further development. As with cobalt-based, these batteries have safety implications and require sophisticated battery management [14].

2.4.6. Fuel cells

Fuel cells use electrochemical energy conversion to store and generate electricity. Electricity is produced when the fuel (anode) and oxidant (cathode) react in the presence of an electrolyte. Typically during operation, reactants will flow in, products of reaction will flow out while the electrolyte remains in the cell. Energy is produced continually while the flow of reactants and products is maintained. Fuel cells differ from batteries in that reactants are consumed and must be replenished. Reversible fuel cells are designed so that the reactant and electrolyte produce electricity plus products, which can be reversed by the addition of electricity to change the product back into the initial reactant. The catalytic electrodes in a fuel cell are relatively stable. In hydrogen fuel cells, hydrogen acts as the reactant and oxygen as the oxidant to form water and electricity.

Fuel cells offer several advantages of having very high energy density, applicability at small and large-scale and simple modular use, however they are currently expensive and suffer from a very low round trip efficiency [1]. A fuel cell is an appropriate way to use hydrogen. Off-peak renewable power can be used to power an electrolyser unit, producing hydrogen and oxygen from water. Hydrogen can be separated and stored and then used as required in a fuel cell to generate electricity. Application a fuel cell as the power generator is the most energy efficient means of electricity production from hydrogen [1].

3. Comparison of energy storage technologies

In the current work, available data on efficiency, energy capacity, energy density, run time, capital investment costs, response time, lifetime in years and cycles, self discharge and maturity of each major energy storage option was collected from the literature to the extent possible and is summarised in Table 1. Flywheels, supercapacitors and SMES show the highest maximum efficiency, and fastest response times, however they also have among the highest capital costs expressed in $/kWh due to short operating times. Pumped hydro storage systems have the highest capacity by a large margin, but are also among the least energy dense storage options. The technologies capable of providing continuous electricity supply for 24 h or more are underground compressed air energy storage (CAES), pumped hydro, fuel cells and high temperature thermal energy storage systems (HT-TES).

Pumped hydro storage and CAES have the lowest investment risks with respect to the cost per kilowatt hour of electricity produced and the lowest levelised cost of delivered energy, comparable with combined cycle gas turbines [9]. However, they are expensive to site and build, with long construction time, only suitable for large scales [14], have low energy density [10] and typically result in long transmission distances [15]. Fuel cells offer the highest energy density, however the capital cost is the largest among all energy storage options with one of the lowest energy conversion efficiency ranges.

In order to provide smooth and uninterrupted electricity supplies, it is necessary to combine several different energy management strategies. Power quality management, load shifting and standby reserve are all necessary to maximise the efficiency and reliability of the system. Each has very different desirable characteristics and the most appropriate energy storage systems will vary according to the desired role in the power management strategy.

Power quality management relies on very fast response times to smooth electricity quality disturbances on a nanosecond and millisecond scale to provide uninterrupted, reliable power. The best examples for this application are flywheels, capacitors and SMES due to very fast response rates and the ability to be charged and discharged frequently whilst maintaining good operating lifetimes.

Load shifting involves storing energy available in times of lower electricity demand and storing this for peak demand times. Thermal energy storage is well suited to load shifting due to low costs and good capacity, whilst batteries are most commonly used in this application.

Standby reserve is an available reserve of power that can be brought online to take over from the main power generating source if it should fail or become unavailable. Ideal energy storage systems must hold their charge for long time periods and have the ability to operate for days without interruption. PHS and CAES have the largest capacity and low self-discharge, making them ideally suited to this application and the only technologies currently proven for utility standby reserve. Technologies under development that will likely be appropriate in the future include fuel cells and high temperature batteries such as Na–S.

For maximum power reliability, a combination of storage methods is necessary, including short and long-term storage. Some technologies are able to fill more than one role, for example advanced batteries are fast responding and can operate for hours,

Table 1
Summary of energy storage technologies.

	Efficiency (%)	Capacity (MW)	Energy density (Wh/kg)	Run time (ms/s/m/h)	Capital ($/kW)	Capital ($/kWh)	Response time	Lifetime (Years)	Lifetime cycles	Self discharge (per day)	Maturity	Charge time	Environmental impact	Thermal needs	References
Mechanical storage															
CAES underground	70–89	5–400	30–60	1–24+ h	800	50	Fast	20–40	>13,000	Small	Commercial	Hours	Large	Cooling	[1,2,10,12,31,38,39,43]
CAES aboveground	50	3–15		2–4 h	2000	100	Fast	20–40	>13,000	Small	Developed	Hours	Moderate	Cooling	[9,40]
Pumped hydro	75–85	100–5000	0.5–1.5	1–24+ h	600	100	Fast	40–60	>13,000	Very small	Mature	Hours	Large	None	[2,30,31,38,39,43]
Flywheels	93–95	0.25	10–30	ms-15 m	350	5000	Very fast (<4 ms)	~15	>100,000	100%	Demonstration	Minutes	Benign	Liquid nitrogen	[1,14,30,31,38,43]
Electrical storage															
Capacitor	60–65	0.05	0.05–5	ms-60 m	400	1000	Very fast	~5	>50,000	40%	Developed	Seconds	Small	None	[1,31,47]
Supercapacitor	90–95	0.3	2.5–15	ms-60 m	300	2000	Very fast	20+	>100,000	20–40%	Developed	Seconds	Small	None	[1,38,39,43]
SMES	95–98	0.1–10	0.5–5	ms-8 s	300	10,000	Very fast (<3 ms)	20+	>100,000	10–15%	Developed	Minutes to hours	Moderate	Liquid helium	[1,31,38,43,48]
Thermal storage															
CES	40–50	0.1–300	150–250	1–8 h	300	30		20–40	>13,000	0.5–1%	Developing	Hours	Benign	Thermal store	[1,11]
HT-TES	30–60	0–60	80–200	1–24+ h		60		5–15	>13,000	0.05–1%	Developed	Hours	Small	Thermal store	[1,22,33,42,46]
Chemical storage															
Pb-acid battery	70–90	0–40	30–50	s-h	300	400	Fast (ms)	5–15	2000	0.1–0.3%	Mature	Hours	Moderate	Air conditioning	[1,9,34,38,39]
Na–S battery	80–90	0.05–8	150–240	s-h	3000	500	Fast (ms)	10–15	4500	~20%	Commercial	Hours	Moderate	Heating	[14,34,36,38–41]
Ni–Cd battery	60–65	0–40	50–75	s-h	1500	1500	Fast (ms)	10–20	3000	0.2–0.6%	Commercial	Hours	Moderate	Air conditioning	[1,17,34]
Li-ion battery	85–90	0.1	75–200	m-h	4000	2500	Fast (ms)	5–15	4500	0.1–0.3%	Demonstration		Moderate	Air conditioning	[1,10,32,34,37,38]
Fuel cells	20–50	0–50	800–10,000	s-24+ h	10,000		Good (<1 s)	5–15	>1000	Almost zero	Developing	Hours	Small	Varies	[1,29,30,35,44,45]

making them suitable for power quality management, load shifting and medium term standby reserves.

There have been many studies on the optimal combination of electricity generation and storage. Most have focused on combinations of wind, solar or hydro with compressed air energy storage [31,49,50], pumped hydro energy storage [51–53] or batteries [23,36,54], or coupled thermal storage with thermal technologies including concentrated solar power [2,22,55–57], nuclear [58] and fossil fuels [58]. Indirect storage through generation of hydrogen is also often discussed [6,35,59–62]. It is obvious that system efficiencies will increase when energy is generated and sent directly to storage in its original form, such as the coupling of mechanical and thermal power generation technologies with mechanical and thermal storage technologies, respectively. Such is the case when excess energy from concentrated solar power is stored using thermal energy storage, or excess wind energy is used as a mechanical driver for compressed air energy storage.

As shown by Denholm and Kulcinski [58] the choice of generation and storage combination effects the greenhouse gas emissions of the system. Coupling of pumped hydro energy storage and nuclear or renewable technologies produced fewer emissions than with compressed air energy storage or batteries, whereas the combination of compressed air energy storage with fossil fuels produced significantly less emissions than fossil fuels with pumped hydro energy system or batteries. As discussed by Hessami and Bowly [63], preference of one storage method over another is site specific and must account for local conditions. Where such considerations are made, energy storage can potentially prove a significantly important and profitable addition to an energy management system.

4. Conclusion

There is a range of options available to store intermittent energy until it is needed for electricity production. As the percentage of renewable energy sources in the grid continues to increase, the storage methods will become critical to the provision of secure and uninterrupted power. With further use of storage, prices and efficiencies will become more favourable, such that coupled renewable and storage energy systems will be economical. The choice of storage system will depend on the individual needs, however it will commonly be necessary to incorporate more than one energy storage in systems providing large amounts of energy. In this way, both short and longer term power interruptions can be compensated from stored energy. Continuing investment and research in this area will help to mark the way for greater use of renewable energy sources in future electricity supply grids.

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